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CHARACTERIZATION OF GRAPHITE ELECTRODES

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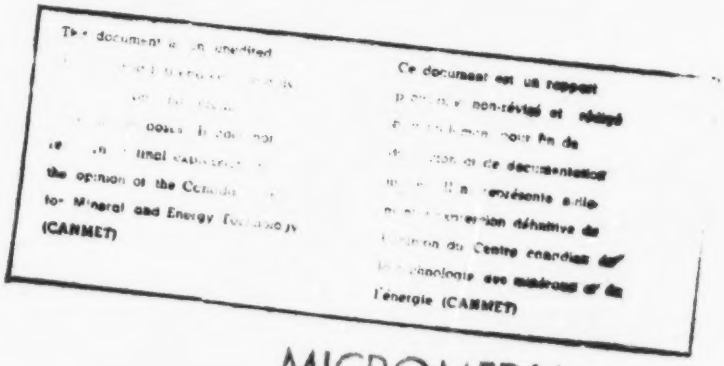

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CHARACTERIZATION OF GRAPHITE ELECTRODES

by

D.H.H. Quon* and K.E. Bell**

ABSTRACT

Preliminary study in characterization of graphite electrodes has demonstrated that both pulse velocity and eddy current tests are suitable techniques for assessing the physical characteristics of the electrodes. These two techniques are non-destructive and less time consuming than other techniques currently used for electrode characterization.

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CARACTÉRISATION DES ÉLECTRODES EN GRAPHITE

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RÉSUMÉ

Des études préliminaires portant sur la caractérisation des électrodes en graphite indiquent que les essais relatifs à la vitesse des impulsions et aux courants de Foucault sont des techniques appropriées pour faire l'évaluation des caractéristiques physiques des électrodes. Ces deux techniques sont non destructives et plus rapides que d'autres techniques que l'on utilise actuellement pour la caractérisation des électrodes en graphite.

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INTRODUCTION

Graphite electrodes represent one of the highest operating costs in electric arc steelmaking. Their cost, estimated by electrode consumption on the order of 4.5 kg/t of steel, varies from 15-30% of the total operating cost of a dc electric arc furnace (1). This represents approximately 8% of the operating cost for the steel refining process. Increases in refining cost can be related to the energy concentration of the materials and manufacturing process. Thus, it is not surprising that considerable effort is being directed to the subject of electrode consumption and how it may be minimized. Electrode wear in the arc furnace can be generally classified in three major categories (2):

1. tip consumption,
2. surface consumption,
3. intermittent consumption.

It has been reported that the electrode consumption is proportional to the magnitude of the electric current to the power of 1.5 to 2. The surface consumption of the electrode depends on the total surface area of the electrode exposed to the furnace gases, oxygen content and velocity of these gases, the surface temperature of the electrode and exposure time, i.e., effectively the tap-to-tap time (3-6). One of these parameters, tap-to-tap time, is affected by the method of furnace operation. Good furnace control, coupled with efficient oxygen lancing, reduces oxygen content of the furnace gases. The exposed surface area of the electrode may be controlled by reducing furnace height, with a water-cooled roof and electrode, or by use of electrode coatings to protect the graphite from oxidation.

Intermittent consumption of electrodes is related to losses due to electrode breakage, which is mainly caused by mechanical or thermal stresses.

It is apparent that electrode consumption is related to the operating conditions of the electric arc furnace. Thus temperature, slag attack and/or erosion, oxidation, and macrospalling due to mechanical loading and thermal shock can strongly influence the loss rate. The extent of the contribution of each factor can vary enormously from furnace to furnace, depending on furnace design, the particular process in vogue and raw materials used, and their metallurgical implications at each stage of processing. Although electrode

consumption can be and is measured, in terms of kg of graphite per tonne of steel produced, during any interval of reasonably constant operating conditions, it is difficult to separate the effect of variances in electrode quality. Laboratory furnaces capable of duplicating the wide variety of operating conditions in industry are not available and, if they were, considerations of scale would appear to render them of questionable practicability. Hence, the effect of operating parameters must be inferred from simpler tests such as oxidation rates in air or simulated furnace atmospheres.

It has also been cited that a number of physical properties are directly or interdependently related to electrode consumption, as electrode quality varies from manufacturer to manufacturer as well as from batch to batch and even within a single electrode (3). The physical and electrical characteristics of the electrodes depend on the manufacturing procedures, particularly relative to: 1) the nature of the raw materials (petroleum coke) employed, which determines the final basic physical properties (12); and 2) the graphitization process, which provides high axial electrical conductivity and good resistance to thermal stresses. Quantitative information on the petroleum-coke/electrode-quality interaction is not available, nor is a clear differentiation of the influence of the many processing steps involved in graphite manufacturing.

Canadian industry has recognized the difficulties in predicting electrode consumption and the associated costs, and the Canadian Iron and Steel Research Association (CSIRA) has identified a need for R & D to develop test methods suitable for characterizing electrodes and predicting their service behaviour, which would serve as acceptance tests for shipments received. In response, CANMET initiated a project to evaluate the physical and electrical properties of typical electrode materials as a means of identifying those properties that might be correlated with service peformance and thus delineate test methodologies required: emphasis was planned on electron-optical examination of microstructures, which has been little reported previously.

PREVIOUS WORK

Several studies have reported on various graphite properties and evaluation of electrodes on the basis of electrical resistivity, apparent density, flexural strength, etc. (6-10). Some of these techniques have been adopted as routine tests in many steel plants and provide some guidance as to

the properties considered critical to electrode performance. Usually, the tests are performed on samples cored from the root of the connector threads, thus do not reflect within-electrode variations nor reveal any gross flaws or weaknesses that could lead to breakage. Those properties most frequently measured are: apparent density, apparent porosity, apparent specific gravity, electrical resistivity (longitudinal and transverse), and flexural strength.

Scroth et al., based on field tests, found that a number of physical properties of electrodes can be correlated with consumption (7, 8). Consumption increases as the apparent density decreases, or conversely as porosity increases; consumption decreases as flexural strength and longitudinal and transverse resistivity increases.

More recently, non-destructive techniques using eddy-current and pulse-velocity measurements have been evaluated for characterizing electrode quality.

EXPERIMENTAL

The principal aim of this work was to characterize typical graphite electrodes by means comensurate with in-plant testing, and to seek correlation between the measured properties and service performance.

MATERIALS

The graphite electrodes used for this study were obtained from commercial suppliers. Two different sizes of electrodes were examined: 3.8 cm diameter by 61 cm in length, and 13 cm diameter by 105 cm in length. Core samples from 51 cm diameter electrodes, and plant-derived data for same, were provided by a cooperating Canadian steel company. Samples and data represented products from three suppliers, rated "acceptable", "better" and "best" (Japanese) by the company.

CHARACTERIZATION

Selected tests conducted on the graphite electrodes were: 1) Bulk density, 2) Specific resistance, 3) Compressive strength, 4) Modulus of rupture, 5) Specific resistance, 6) Thermal expansion, 7) Oxidation rate with temperature, 8) Pulse velocity, 9) Eddy current test, and 10) Microstructure.

Both bulk density and apparent porosity of the electrodes were determined according to ASTM C373-72.

The compressive strength and modulus of rupture of the electrodes were determined using the ASTM procedures C695-71T and C133-72 respectively.

The specific resistance of the electrodes was measured according to ASTM C611-69 with minor modification. A schematic diagram of the resistivity measurement apparatus is shown in Fig. 1.

The thermal expansion of the electrodes was measured according to ASTM C372-76.

The rate of graphite oxidation was determined by heating a small graphite sample (1x1x1 cm) in air at constant temperatures of 500, 650, 700 and 750°C for a period of 5 hours. The weight loss at these temperatures and time is assumed to be loss due to oxidation of the graphite.

Ultrasonic pulse velocity was used to determine the transit time of ultrasonic pulses through the graphite electrode and was used to establish the dependence of pulse-transit velocity on strength. The equipment used is commercially available and known as PUNDIT.

Eddy current testing of the electrodes was based on the technique developed by Roach (9). In this test, the interaction between an electromagnetic field and the materials was measured. In this technique, currents are induced to flow in the electrode by an external coil. This current is partially absorbed by the electrode and converted into heat by the effect of resistivity and hysteresis. Part of the remaining energy is reflected back to the test coil; its electrical characteristics change in a manner determined by the properties of the specimen being tested. Consequently, the currents flowing through the probe coil represent the source information describing the characteristics of the material under test. Those currents are analyzed and compared with currents flowing in a reference material, resulting in the form of number on a scale. This technique has been adopted for quality control of electrodes in some steel plants. It is a convenient method to quickly measure electrical resistivity. A portable eddy current tester, Verimet model M1900, used for this study was on loan from K.J. Law Engineers, Inc.

Microstructures of the graphite electrodes were examined in polished section using either optical (OM) or scanning electron microscopy (SEM).

RESULTS

BULK DENSITY AND APPARENT POROSITY

Bulk density of the graphite is a significant property in two respects. Physically, there is a strong relationship between density of graphite and such properties as Young's modulus, flexural strength, thermal expansion, and resistivity. Generally, an increased density is reflected by improved mechanical and thermal characteristics. However, high density itself is not an assurance of successful structural and thermal performance. Increasing density and decreasing porosity also reduces the thermal shock resistance. Optimization of these two parameters is necessary to reduce thermal shock and to retard crack propagation. Density of commercial graphite varies from 1820 to 1850 kg/m^3, and flexural strength is commonly between 1500 and 1700 kg/m^3. As may be expected, density and porosity are important as they control the strength of the electrode.

Tables 1, 2 and 3 give the densities measured for 3.8 and 13 cm diameter electrodes and include density data supplied by a steel plant for 51 cm diameter electrodes. It can be seen from the tables that the density of these electrodes varies with electrode size and thus, presumably, with manufacturing technique. The variation in density noted for the large electrodes is of considerable significance as they were obtained from three different suppliers. The test results show that the density of the electrodes varied not only between manufacturers but also within each batch.

It is well documented that conventional graphite electrodes have less than optimum resistance to ablation and have a low degree of reproducibility and structural uniformity. When compared with pyrolitic graphite for oxidation resistance, the electrode graphite is considerably lower due to the extensive voids and pores present, resulting from the loss of volatiles from the filler material in the graphitization process and from contraction during cooling along the a and c crystallographic directions. Porosity provides information as to the effectiveness of impregnation and process control in the manufacturing process, and therefore it is a very important physical parameter; both the open and closed pores can affect the performance of the electrodes. The apparent porosity for the different-sized electrodes were measured and the data obtained from the measurements are given in Tables 1-3. The results show that the calculated apparent porosity varies from 12.7 to 21% and varied from supplier to supplier as well as within each group of electrodes.

Based on the variation in density and porosity data for the different electrode sizes and groups, further work was conducted to determine the density and porosity variation within a single electrode. Test samples were taken at the middle and at the extreme right and left ends along the length of the electrode. The measured density and porosity of the electrodes are given in Table 4. The results demonstrated that these two parameters varied from end to end of the electrode.

COMPRESSIVE STRENGTH AND MODULUS OF RUPTURE

Both cold compressive strength and modulus of rupture of the graphite electrodes have been correlated with electrode consumption by Scrotn (7). He reported that the consumption increases with decrease in both cold compressive strength and modulus of rupture. Cold compression and modulus of rupture tests on 13 cm diameter electrodes were conducted and the results obtained are given in Table 5. As can be seen, the cold compressive strength of the electrode varied from 36.6 to 44.3 MPa and the modulus of rupture vaired from 28.4 to 31.5 MPa. The data of the modulus of rupture for the steel plant electrodes are given in Table 3, and they show a variation from 7.2 to 10.1 MPa. There is also an evident variation between electrodes obtained from different suppliers.

SPECIFIC RESISTANCE

Previous investigators attributed electrode side-wall losses mainly to oxidation and, to a certain extent, to the temperature of the electrode. The electrode temperature is generated by resistance heating, at least until the furnace temperature is sufficiently high for radiation to the electrode to be the dominant effect. Thus, the resistivity can be expected to influence electrode temperature and hence side-wall loss. Both laboratory and pilot studies on the tip losses and current flow of the electrode vs. the resistivity found that resistivity is positively but weakly correlated to consumption (6, 14). The consumption can be significantly reduced by using electrodes of low resistivity. It has been pointed out by other investigators that, for resistivity tests, the technique of sampling of the electrode is important in obtaining meaningful results. In the standard test, a core sample was obtained from the electrode as it is generally believed that the core resistivity is more representative of the complete electrode section. However,

work conducted by Nicholson et al. demonstrated that the core resistivity need not be representative of the complete electrode section (11). Because the electrode diameters of 3.8 and 13 cm used for this study are relatively small, the resistivity measurements were obtained from the wall of the electrode. Typical electrical resistivity data for the 13 cm diameter electrodes are plotted in Fig. 2 and 3. For some electrodes, the end-to-end resistivity appears to be fairly uniform whereas others varied markedly. The average resistivity for each electrode was calculated and the results are given in Table 1: these values were obtained by averaging resistivity measurements from end to end of each electrode. As to be expected, the average resistivity of these electrodes varied from 6.8 to 9.8 μ ohm.cm.

Data of the core resistivity for the steel plant electrodes from three different suppliers are given in Table 3. Marked differences in resistivities for electrodes from the various suppliers are readily apparent.

Transverse electrical resistivity variation of the electrode was also determined. In this test, samples were obtained from the cross section at left end, right end and middle of the electrodes. The results of the measurements, given in Table 3, show that the resistivity of the electrodes also vary markedly in the transverse section.

THERMAL EXPANSION

Thermal expansion from room temperature up to 800°C for the 13 cm electrodes were measured. Test samples were fabricated from the left and right along both the longitudinal and transverse section of the electrode. The results of the linear expansion versus temperature for different sample orientations are plotted in Fig. 4 and 5. The results indicate that the linear thermal coefficient of expansion varies in both longitudinal and transverse directions. Furthermore the thermal expansion is significantly greater in the transverse than in the longitudinal direction. This is considered to be a function of particle orientation resulting from the fabrication method employed, probably extrusion, and reflects the anisotropy of the graphite crystals.

OXIDATION LOSS

The weight losses of electrodes due to oxidation at four different temperatures with a constant soak time of 5 hours are given in Table 7. No

appreciable weight loss occurred at temperatures below 500°C. At various temperatures above 500°C, some electrodes started to lose weight more rapidly than others. The cause of the differences in the oxidation behaviour is unclear, as there is no apparent correlation with any of the other physical properties measured.

The weight loss data for the steel plant electrodes from UC, GLC and NGK are given in Table 7. The rate of oxidation loss is attributed to the nature of the carbon, impurities present, particle size and degree of graphitization. The low resistivity, high porosity and low oxidation loss of the NGK electrode indicated that the material has a greater preferential alignment of the crystals resulting from a higher degree of graphitization.

PULSE VELOCITY

Ultrasonic pulse velocity has been used as a non-destructive test for monitoring graphite electrodes, to eliminate inferior electrodes before use and to predict performance quantitatively. It has been demonstrated that low pulse velocity values correlate with electrodes having low modulus of elasticity and flexural strength (10).

The results of the pulse velocity measurements for the 13 cm diameter electrodes, given in Table 1, show that these values varied from electrode to electrode from a minimum of 2.78 to a maximum of 2.96 km/s.

EDDY CURRENT TESTING

Eddy current testing techniques were introduced by Roach as a non-destructive method in monitoring the quality of graphite electrodes, and have been used to assess the physical properties of the electrodes including the porosity and grain orientation (9). Other workers reported that the technique represents a convenient method to quickly measure electrical resistivity (7, 8).

Data obtained from the eddy current reading for the 13 cm diameter electrodes are given in Table 1. These values vary from a minimum of 420 to a maximum of 530. Typical variation of eddy current measured along the length of the electrodes at 6 cm intervals is plotted in Fig. 6. Figure 7 is a plot of resistivities versus eddy current readings at 10 kHz for different electrodes. The results show a general correlation of these two parameters and indicate that electrodes of high resistivity have a low eddy current reading.

Eddy current data for the 51 cm diameter electrodes currently used in the steel plant are given in Table 3. The results indicate that the eddy current values vary from a minimum of 683 to a maximum of 723. Apart from the different values for electrodes from different suppliers, there is also a noticeable difference in eddy current readings for electrodes obtained from the same supplier. The resistivity versus eddy current readings of the various 51 cm electrodes are plotted in Fig. 8 and show a general correlation between these two parameters.

MICROSTRUCTURES

One factor influencing the quality of the electrode is the microstructure. The grain size of the graphite, orientation effects, the pore form, and the changes of the filler materials as a result of graphitization, can only be revealed by microstructure examination.

The structure of the graphite electrodes, as revealed by optical microscopy is lamellar, with fine granules and pores formed in the interstices (Fig. 9 to 11).

Under the scanning electron microscope (SEM), it was observed that the structure varies in both longitudinal and transverse section of the electrode. A SEM micrograph of a fracture surface of an electrode is shown in Fig. 12. At high magnification, at the right longitudinal section of the electrode, the graphite crystals are oriented in the (0001) direction and parallel to the electrode length (Fig. 13). At the left longitudinal section of the electrode, the graphite crystals show lamellar structure (Fig. 14). The densely packed oriented crystals may in fact give rise to low resistivity readings and the randomly oriented crystals give rise to high resistivity readings due to the crystal anisotropy. In some electrodes, it is not uncommon to see structures also composed of randomly oriented grains (Fig. 15 and 16). It is not possible to correlate the orientation effect with resistivity changes of the electrode as there is too much localized structural variation. The two textures commonly reported in the literature as either lamellar or scaly are merely differences in crystal orientation. The differences in the structure in the longitudinal and transverse sections is attributed to the extrusion process. The preferential alignment of the graphite particles changes the volume of the pores in the electrode. Other factors such as grain size, etc., can influence the physical properties such as resis-

tivity, coefficient of expansion, and strength of the materials. Although microscopy can provide valuable information as to the physical characteristics of the electrode, the localized variations make it too unreliable to use as a rapid, convenient technique for electrode characterization.

DISCUSSION

The current standard techniques used for electrode characterization in steel plants are: (1) bulk density, (2) apparent porosity, (3) electrical resistivity, (4) modulus of rupture, (5) thermal expansion, and occasionally (6) eddy current. In addition to the above techniques, pulse velocity was introduced in this work.

Preliminary results of the work conducted in this laboratory, as well as the test data supplied by a steelmaker, have demonstrated that there are several techniques that are suitable for characterizing the physical properties of the electrodes.

A positive correlation between resistivity and the eddy current test has been established. It shows that electrodes with high eddy current readings have low resistivities. Figure 17 shows a plot of modulus of rupture versus eddy current reading of the steel plant electrodes, indicating that the eddy current reading increases with increasing modulus of rupture. Therefore, the eddy current test can be used as a rapid technique to evaluate the resistivity and the modulus of ruputure of the electrode.

The porosity of the electrode is an important parameter related to the electrode performance. It has been reported that consumption increases with increasing porosity and decreasing modulus of rupture. Pulse velocity versus apparent density of the electrode is shown graphically in Fig. 18 and 19 for the different electrode sizes. The poor correlation of these parameters is reflected in these figures and has been ascribed to inability to obtain accurate calculated density due to localized density variations within the electrode, i.e., the measured apparent density represents only the localized density of the core sample. For small electrodes, where both density and porosity can be more easily determined with reasonable accuracy, the plots of pulse velocity versus density and porosity of the electrodes show a weak, but significant correlation of these parameters (Fig. 18 and 19). It is apparent from these data that the higher the density and lower the porosity, the faster

is the transit time of the ultrasonic pulse passing through the materials. Therefore, a low-porosity electrode has a higher strength. The pulse velocity technique is a rapid non-destructive test and is recommended for routine assessment of the electrodes (7, 8).

It has been shown that the linear thermal expansion of the graphite electrodes varied in longitudinal and transverse sections. These variations reflect the non-uniformity of the structure of the electrode, presumably due to the crystal orientation effects as well as pore distribution, which are related to the manufacturing process.

SUMMARY

Preliminary studies in characterization of graphite electrodes have shown that both pulse velocity and eddy current tests are suitable non-destructive techniques for assessing the quality of electrodes. These techniques are relatively simple and less time consuming than most others. To determine their utility as acceptance tests, in-plant studies should be conducted to establish their relationship to electrode consumption.

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Table 1 - Physical properties of 13-cm diameter electrodes

No.	Resistivity (mid)	ohm.cm. 10^{-4} (av)	Pulse vel km/s	Eddy current 10 kHz	Density km/m^3	Porosity %
1	8.44	8.51	2.780		1750	22
2	8.47	8.28	2.907	439.5	1690	25
3	8.57	8.66	2.832		1740	23
4	7.70	7.25	2.785	498.6	1780	21
5	7.54	7.45	2.881	467.8	1780	21
6*	8.66	8.81	2.881	530.0	1750	23
7	8.88	8.90	2.720		1700	25
8	7.23	7.36	2.810		1735	23
9	7.89	7.84	2.850	461.6	1750	23
10	9.12	9.80	2.780		1750	23
11	8.81	8.88	2.840		1740	23
12	7.06	7.19	2.840	492.0	1700	25
13	7.32	7.38	2.840		1732	23
14	7.20	7.23	2.850	477.4	1723	24
15	7.89	8.09	2.793		1724	24
16	7.14	7.20	2.881		1743	23
17	7.84	7.99	2.870	443.1	1724	24
18	8.25	8.37	2.762	486.3	1704	25
19	7.39	7.48	2.810	463.6	1725	24
20	7.40	7.52	2.880	470.6	1719	24
21	7.96	8.09	2.850		1734	23
22	8.89	9.43	2.870		1746	23
23	7.95	8.01	2.960	476.9	1712	24
24	7.36	7.50	2.820	488.8	1709	24
25	8.36	8.61	2.810	440.1	1741	23
26	7.62	7.95	2.780	489.0	1709	24
27	8.11	8.49	2.810	444.6	1728	24
28	7.75	7.99	2.890	462.7	1758	22
29	7.93	8.41	2.790	442.6	1744	23
30	7.60	7.87	2.820		1739	23
31	8.53	8.52	2.870	420.1	1748	23
32	8.02	8.13	2.960		1747	23
33	8.09	8.46	2.850		1735	23

* hollow electrode

Resistivity: (mid) = at middle of electrode,

(av) = average of resistivity measured at 6 cm intervals parallel to the length of the electrode

Calculated density and porosity

Table 2 - Physical characteristics of 3.8-cm electrodes

Sample No.	Resistivity ohm.cm. 10^{-4}	Apparent porosity, %	Apparent density, kg/m^3	Pulse velocity, km/sec
G1	7.95	18.0	1610	2.80
G2	7.92	18.0	1630	2.79
G3	7.88	19.0	1660	2.92
G4	7.57	21.0	1600	2.93
G5	7.60	18.0	1680	3.00
G6	7.95	21.0	1600	2.89
G7	7.66	19.0	1650	2.91
G8	8.35	23.0	1610	2.83

Electrode diameter 3.8 cm, by 61 cm in length.

Probe distance at 2 cm apart.

Table 3 - Core testing of 50-cm diameter electrodes by Atlas Steels Company

	A	B	C	D	E	F	G
NGK							
9	p6	721	54.93	7585	1100	1650	20.3
10	p6	724	48.51	9873	1432	1670	19.8
11	p6	716	49.47	7860	1140	1650	21.0
12	p6	723	48.42	9322	1352	1650	20.5
AV.	p6	723	50.30	8660	1256	1655	20.4
UC							
20	T6	718	60.96	7640	1108	1620	17.3
21	T6	721	58.44	9680	1404	1670	12.7
22	T6	726	58.44	10149	1472	1620	18.1
AV.		722	59.28	9156	1328	1640	15.4
GLC							
2	S6	700	69.85	9763	1416	1690	16.5
8	S6	683	81.28	7226	1048	1670	15.6
11	S6	699	70.50	6895	1000	1670	16.6
24	S6	698	76.20	8274	1200	1630	16.5
6	S6	720	62.23	7336	1064	1630	18.8
17	S6	715	65.72	7860	1140	1630	17.6
19	S6	720	69.35	7886	1160	1650	17.4
AV.		707	69.35	7886	1140	1650	17.4

A = lot number

B = average eddy current at 10^4 Hz

C = resistivity, ohm.cm.10^{-4}

D = modulus of rupture, Kpa

E = modulus of rupture, psi

F = density, kg/m^3

G = porosity, %

Table 4 - Measured density and porosity for 13-cm diameter electrodes

Sample No.	Right	Left	Apparent porosity, %	Apparent density, kg/m^3
B 1	*		12.9	1760
		*	12.5	1760
B 2	*		14.0	1720
		*	12.2	1760
B 3	*		14.2	1780
		*	12.3	1770
B 4	*		12.7	1770
B 5	*		13.7	1755
B 6	*		13.3	1765
B 7	*		15.6	1715
B 8	*		14.6	1735
B 9	*		12.3	1770
B10	*		15.2	1750
		*	14.4	1740
B11	*		12.7	1765
B12	*		12.6	1770

Values based on average of two tests.

Table 5 - Compression and modulus of rupture for 13-cm diameter electrodes

Sample No.	Compression		Modulus of Rupture,	
	psi	Mpa	psi	Mpa
B 7	5339	36.8	4320	29.8
B 8	5297	36.6	4554	31.5
B11	6420	44.3	4413	28.4

Sample size for compression test = 11.4x3.8x6 cm

Sample size for modulus of rupture test = 15.2x2.5x2.5 cm

Table 6 - Variation of resistivity and pulse velocity of electrode perpendicular to the length of the electrode

Sample No.	Left	Middle	Right	Resistivity, ohm.cm. 10^{-4}	Pulse velocity km/s
B1	*			11.28	3.82
		*		10.51	3.80
			*	20.50	3.69
B3	*			16.00	3.70
		*		12.89	3.76
			*	12.84	3.71

Core drill electrode perpendicular to length.

Size of test sample = 12 cm in length by 3.2 cm diameter.

Table 7 - Weight loss of electrodes heated in air at various temperatures

Sample No.	Temp °C	Time h	Wt loss, . %
B 7	500	5	0.18
	650	5	0.35
	700	5	7.10
	750	5	9.47
B 8	500	5	0.38
	650	5	22.00
	700	5	25.80
	750	5	25.00
B11	500	5	0.10
	650	5	3.84
	700	5	2.61
	750	5	20.00
UC	500	5	0
	650	5	10.6
	700	5	11.6
	750	5	17.4
GLC	500	5	0
	650	5	8.4
	700	5	9.6
	750	5	12.2
NGK	500	5	0
	650	5	4.0
	700	5	6.2
	750	5	12.0

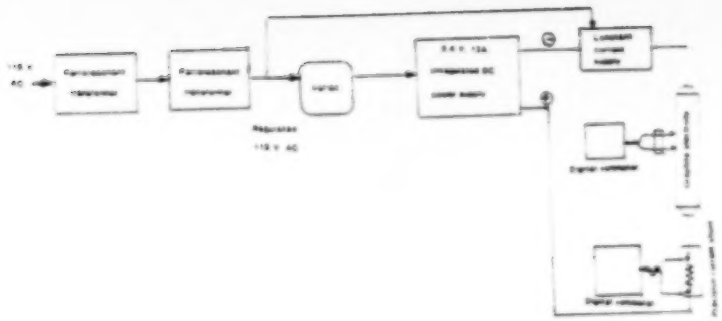

Fig. 1 - Schematic diagram showing the apparatus for resistivity measurements

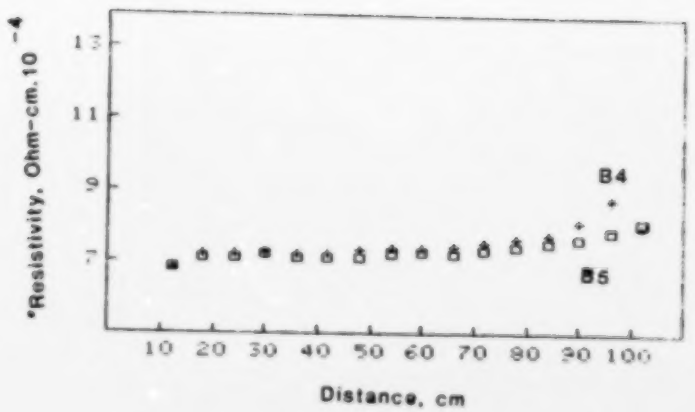

Fig. 2 - Variation of resistivity on longitudinal section of the 13-cm diameter electrodes

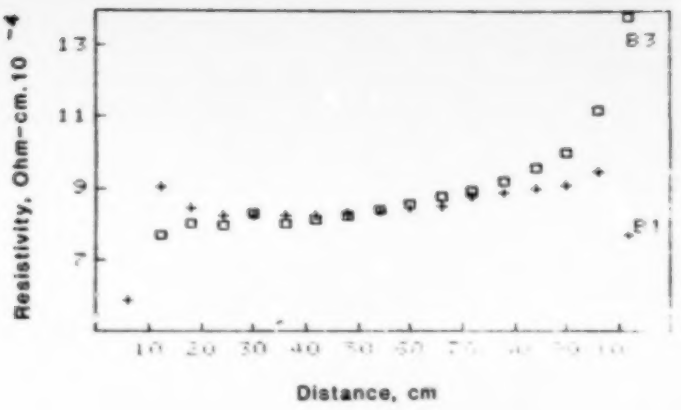

Fig. 3 - Longitudinal resistivity of the 13-cm diameter electrodes

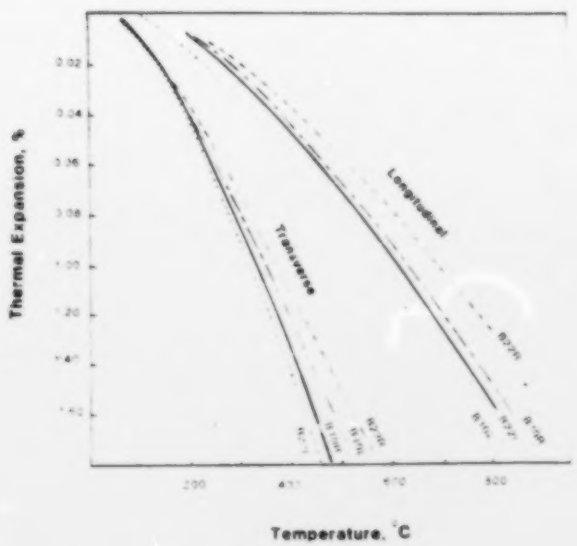

Fig. 4 - Variation of thermal expansion with temperature of the 13-cm diameter electrodes

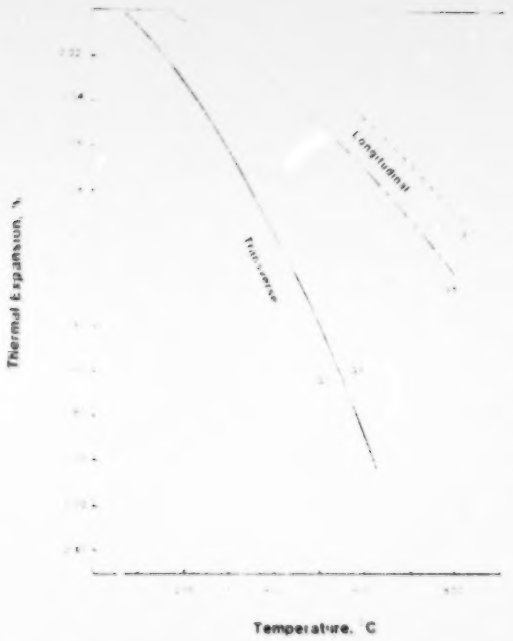

Fig. 5 - Thermal expansion versus temperature for the 3.[illegible]-cm diameter electrodes

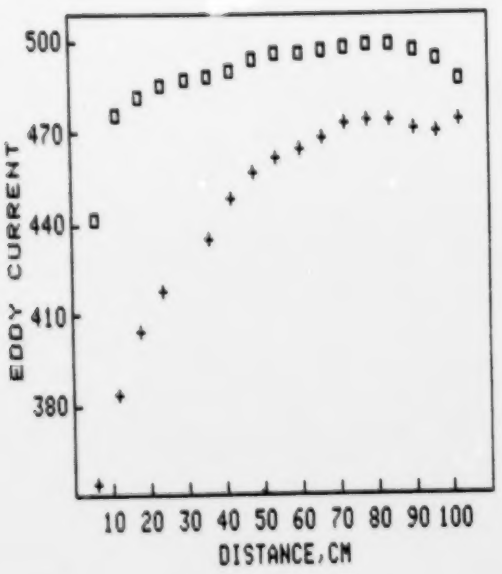

Fig. 6 - Eddy current variation along the longitudinal section of the 13-cm diameter electrodes

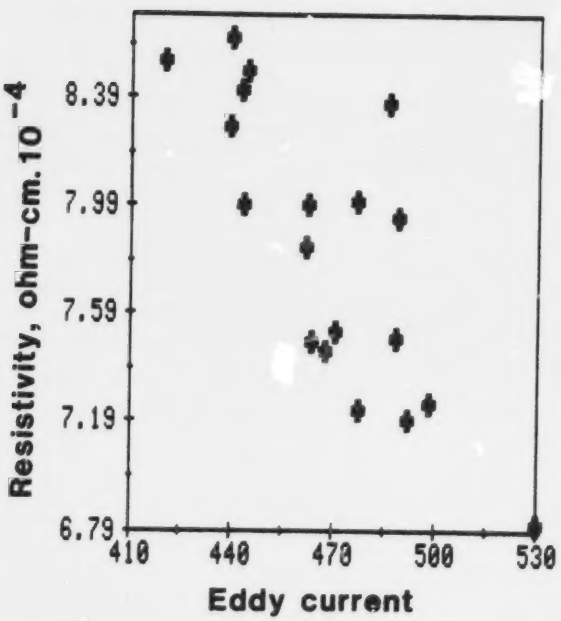

Fig. 7 - Eddy current versus resistivity for the 13-cm diameter electrodes

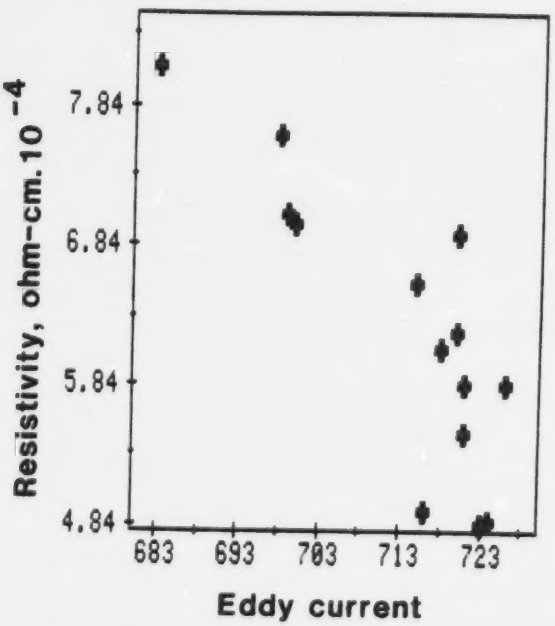

Fig. 8 - Eddy current versus resistivity for the steel plant electrodes

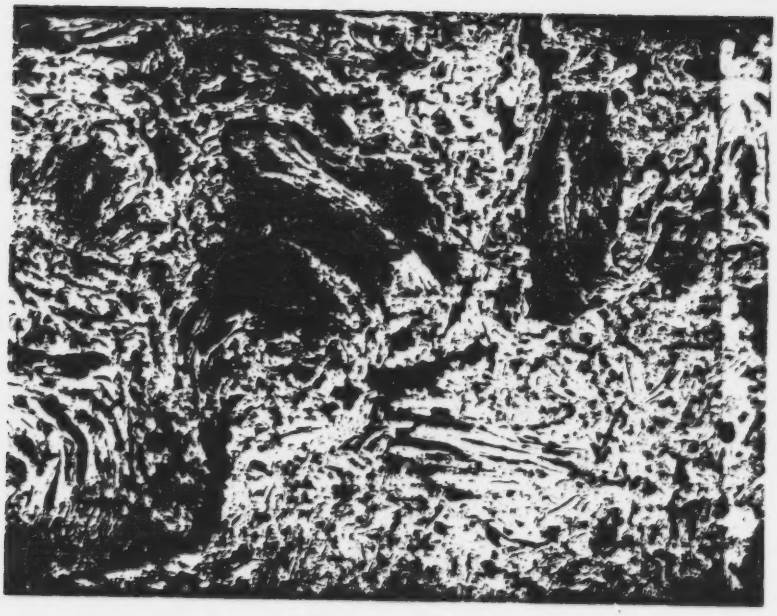

Fig. 9 - Microstructure of the electrode from supplier UC

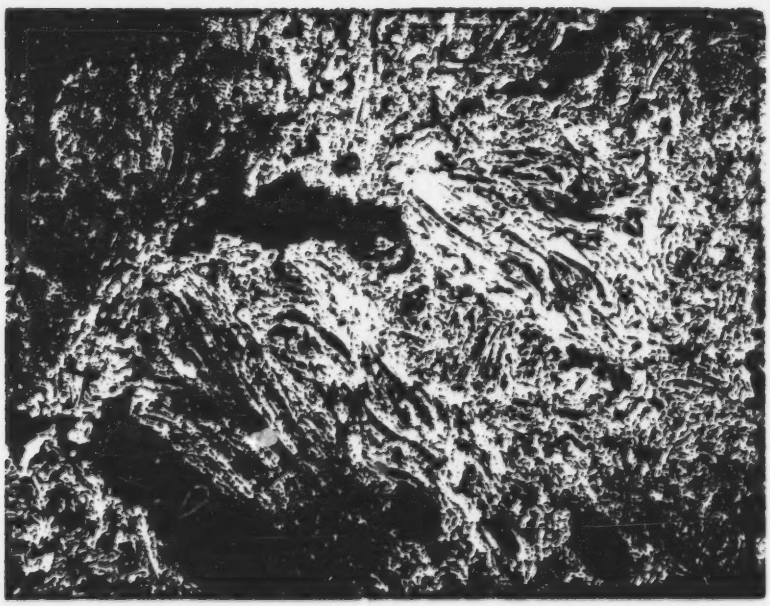

Fig. 10 - Microstructure of the electrode from supplier GLC

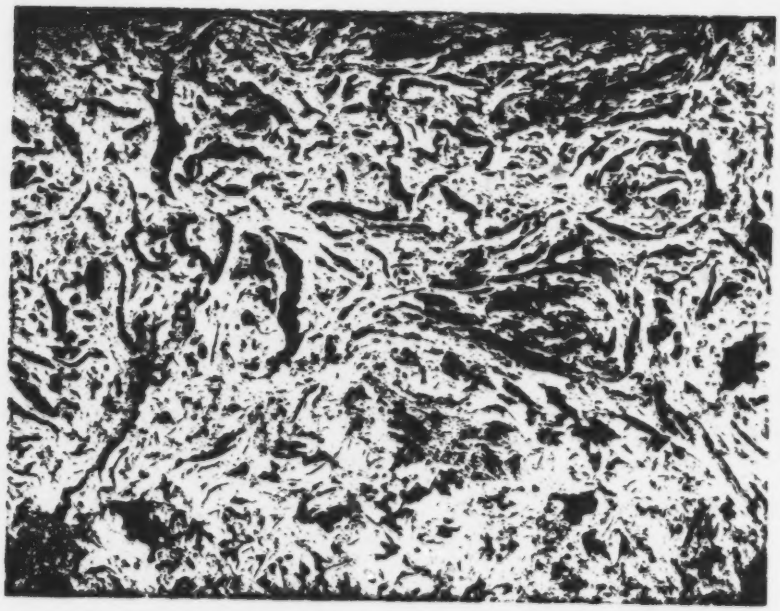

Fig. 11 - Microstructure of the electrode from supplier NGK

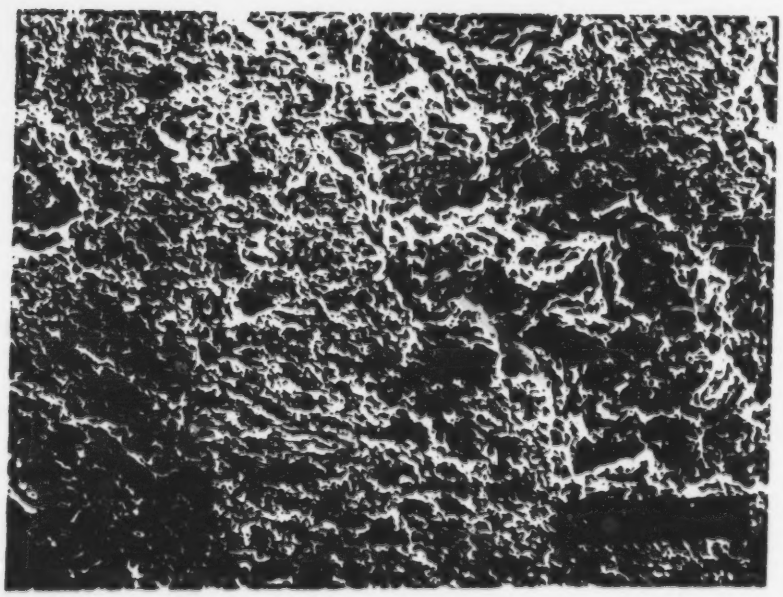

Fig. 12 - SEM micrograph of the fracture surface of a 13-cm diameter electrode

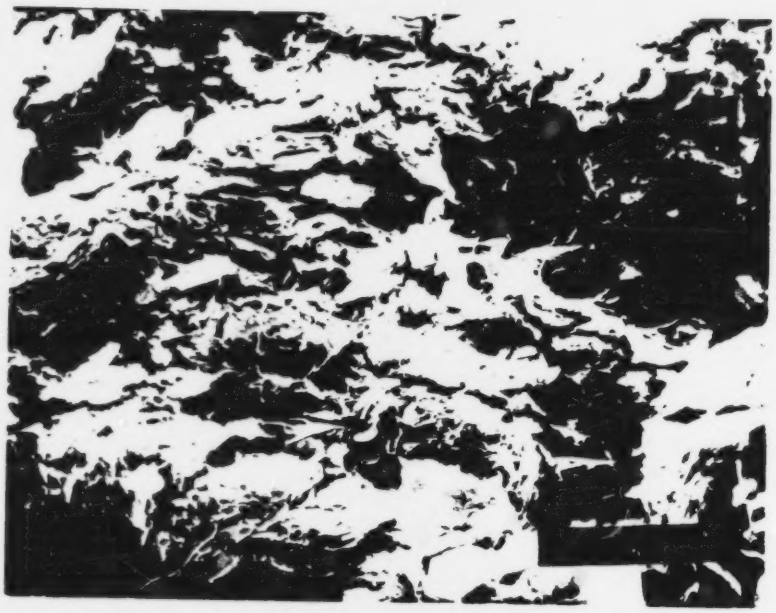

Fig. 13 - SEM micrograph showing oriented platlets of graphite crystals (at longitudinal section)

Fig. 14 - SEM micrograph showing lamellar texture of the graphite electrode (at longitudinal section)

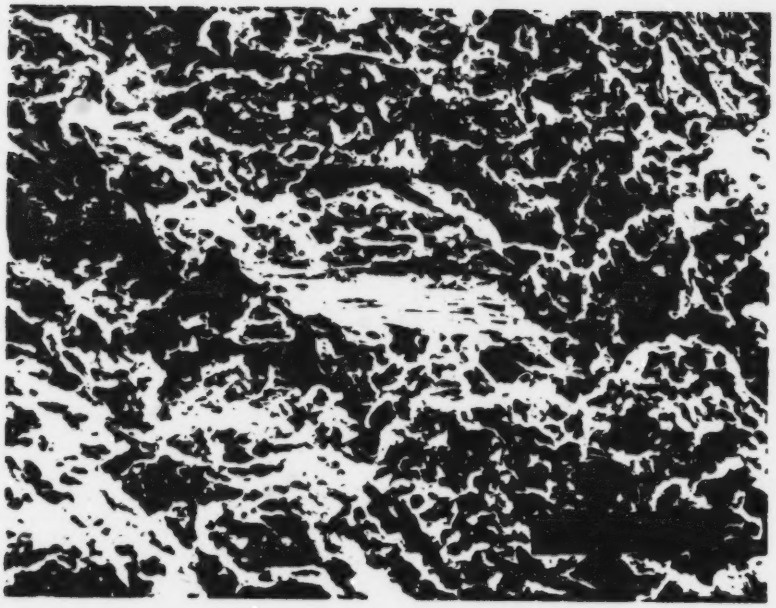

Fig. 15 - SEM micrograph of a fracture surface in the transverse section of a graphite electrode

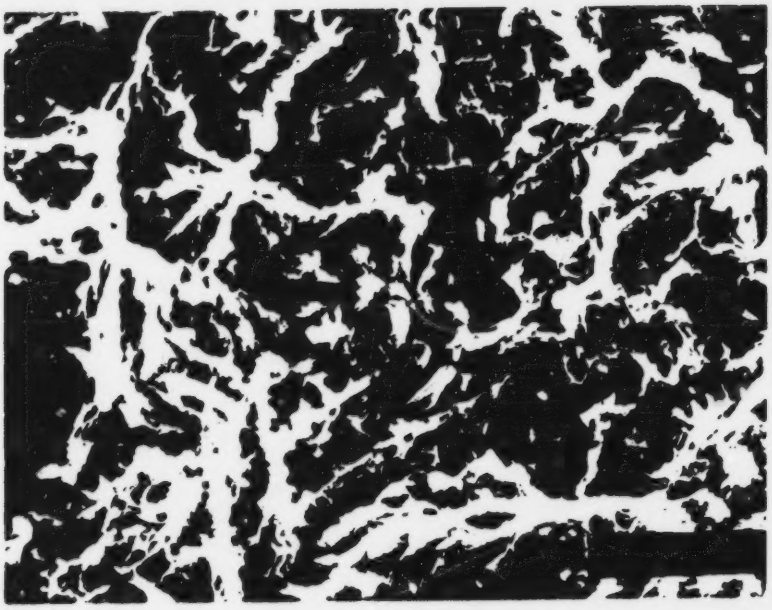

Fig. 16 - SEM micrograph of a fracture surface in the transverse section of a graphite electrode

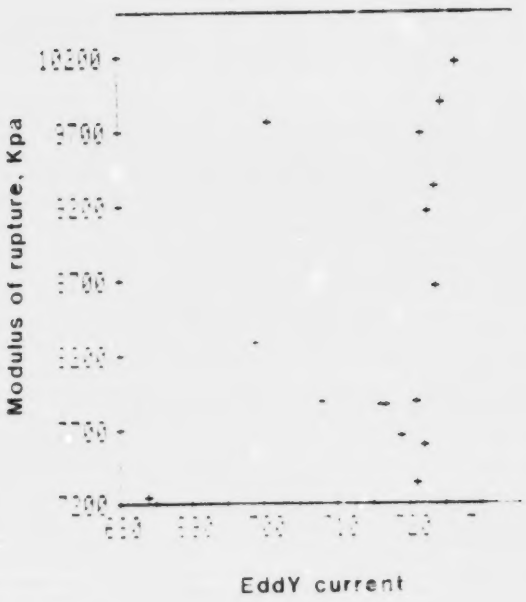

Fig. 17 - Modulus of rupture versus eddy current reading of the steel plant electrodes

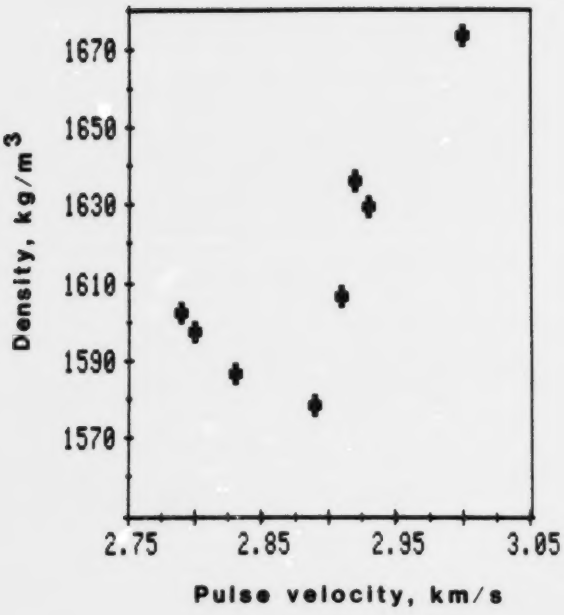

Fig. 18 - Density versus pulse velocity for small electrodes

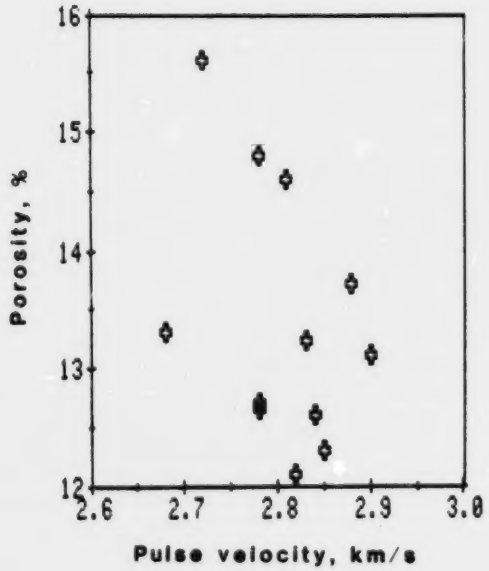

Fig. 19 - Porosity versus pulse velocity for small electrodes